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Abstract
A new approach to microwave eddy current testing for surface cracks in metals involves the use of ferromagnetic resonance in a small garnet crystal placed close to the surface to be tested. It is well known in this case that the induced eddy currents on the metal surface cause a strong displacement of the ferromagnetic resonance frequency. The presence of a crack on the surface produces, by disturbing the eddy current pattern, a perturbation of the resonant frequency as the garnet sample passes over it. Theoretical detectability criteria for the garnet probe are developed on the basis of a magnetic perturbation relation and compared with calculations of Rayleigh wave and plate wave backward scattering and intermode scattering at a half-penny surface crack. Some experimental results are also given.

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NEW METHODS OF DETECTION AND CHARACTERIZATION OF SURFACE FLAWS

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ABSTRACT

A new approach to microwave eddy current testing for surface cracks in metals involves the use of ferromagnetic resonance in a small garnet crystal placed close to the surface to be tested. It is well known in this case that the induced eddy currents on the metal surface cause a strong displacement of the ferromagnetic resonance frequency. The presence of a crack on the surface produces, by disturbing the eddy current pattern, a perturbation of the resonant frequency as the garnet sample passes over it. Theoretical detectability criteria for the garnet probe are developed on the basis of a magnetic perturbation relation and compared with calculations of Rayleigh wave and plate wave backward scattering and intermode scattering at a half-penny surface crack. Some experimental results are also given.

Up to this point the main thrust of research on methods for quantitative NDE has been directed toward internal flaws in materials using primarily ultrasonic methods of testing which provide the most easy access to the interior of an opaque body. In the case of surface flaws, a very important and critical branch of NDE, the flaw is accessible to probing by any one of a number of forms of energy. The purpose of this project is to investigate and evaluate at a fundamental level the use of different forms of energy - ultrasonic, electrical, magnetic, thermal, etc. - for the detection and characterization of surface flaws in materials, and then to explore in detail one or two of the more promising approaches.

After an initial investigation it was determined that eddy current and ultrasound techniques were the best candidates for further study, in that they have high sensitivity and offer the best possibilities for the development of novel approaches to search and characterization procedures. In the domain of eddy currents, microwave techniques have been studied using a ferromagnetic resonator as a probe that provides high sensitivity and spatial resolution, as well as the capability for novel array scanning techniques. The aspect of ultrasonic detection of surface flaws that has been emphasized is the use of guided wave modes to localize the probe on the surface and to deduce additional information about the flaw from intermode scattering.

Ferromagnetic Resonance in Eddy Current Testing

The change in the frequency of a microwave cavity resonator perturbed by a small slot or crack in the enclosing wall according to the Slater formula is

$$\frac{\Delta f}{f} = -\frac{1}{2}\,\frac{\text{magnetic stored energy in crack}}{\text{magnetic stored energy in resonator}} \cdot \quad (1)$$

This shows that the sensitivity of such a crack detection system is enhanced by reducing the volume of the resonator relative to the crack and by increasing the resonator Q.

The ultimate in this regard is a ferrimagnetic resonator, typically taking the form of a yttrium iron garnet (YIG) sample with a volume less than 10^{-4} in^3 and a resonance Q in the order of 1000. Such a resonator does not require an enclosing wall and is readily passed over the metal surface to be tested for cracks.

A resonator of this kind may be used for crack detection by measuring the input impedance at the coupling loop and observing the frequency shift as it passes over the flaw. This method is sensitive to lift off and a better technique is to use a balanced system with two YIG-controlled oscillators. The frequency difference is perturbed by the presence of a crack under one resonator, but is unaffected by changes in lift off d. From the Slater formula the detection sensitivity of a system with typical parameters

$$V_{resonator} = 10^{-4} \text{ in}^3$$
$$d = 0.05 \text{ in.}$$

Short term oscillator stability: 1 part in 10^6 is

$$V_{crack} = 3 \times 10^{-11} \text{ in}^3$$

corresponding to a half-penny shaped crack of radius 15 μm.

In our experiments we have easily detected a long crack 0.006" wide and 0.025" deep, by direct observation of the resonance curve on an oscilloscope. Measurements on cracks of other dimensions confirm that the frequency shift is proportional to the volume of the crack, as predicted by the Slater formula.

The ferrimagnetic resonance technique for surface crack detection provides greater spatial resolution than conventional eddy current testing and a high detection sensitivity. Ferrimagnetic resonators are readily tuned and switched with a small applied magnetic field and are therefore readily adaptable to multi-frequency eddy current testing and scanning. The frequency shift method provides direct digital readout on a counter.

The resonant frequency of an isolated magnetic spin is determined by the restoring torque due to the dc bias field H_0.

In a small magnetic resonator, rf demagnetizing fields, arising from the magnetic poles produced at the boundaries, generate additional torques and shift the processional resonant frequency.

As shown below, the effect of placing a conducting plane in the vicinity of a magnetic resonator is equivalent to that of an image placed an equal distance on the other side of the plane. The torque resulting from action of the image field on the resonator induces an additional frequency shift that varies according to the lift off d.

In a normal bias field configuration the field pattern in (a) rotates without changing form and generates the rotating eddy current distribution in (b). Maximum frequency shift occurs when the crack is normal to the current flow, and cracks of any orientation may be detected directly underneath the resonator.

In a parallel bias field configuration the magnetic field and eddy current distributions alternate between the patterns shown directly above and those shown in the previous figure. Only cracks perpendicular to the bias field direction can be detected.

Resonant frequency detuning caused by a crack in the surface is due to perturbation of the eddy current pattern required to support this field.

Intermode Coupling of Guided Elastic Waves

Attention has recently been directed to the advantages of guided ultrasonic waves in NDE, where selective detection on certain types of flaws may be achieved by a suitable choice of wave mode (W. Mohr and Paul Holler, "On Inspection of Thin Walled Tubes for Transverse and Longitudinal Flaws by Guided Ultrasonic Waves," IEEE Trans. SU-23, pp. 369-374 (1976). By examining scattering between different guided modes one can also extract information about the lateral positions of a flaw in the structure.

Use of the piezoelectric reciprocity relation enables one to derive a simple expression for reflections measured at the electrical input of the ultrasonic transducer (B. A. Auld and G. S. Kino, in preparation) and this may be used to evaluate interscattering effects involving guided modes. An elementary example is normal incidence scattering of SH plate modes from a penny-shaped crack.

The general scattering formula may also be used to calculate normal incidence Rayleigh wave scattering from a half penny-shaped crack on a surface. For a crack of radius a on an aluminum surface, this gives an electrical reflection coefficient

$$\gamma = \frac{1}{2} \eta \frac{a}{w} (ka)^2$$

in the near field where η is the one-way conversion efficiency and w the width of the Rayleigh wave transducer.

For a state-of-the-art Rayleigh wave system this gives a theoretical detection sensitivity corresponding to a half penny-shaped crack with radius in the range of 15 μm. Experimentally cracks with a radius of several hundred μm have been observed.

Acknowledgement

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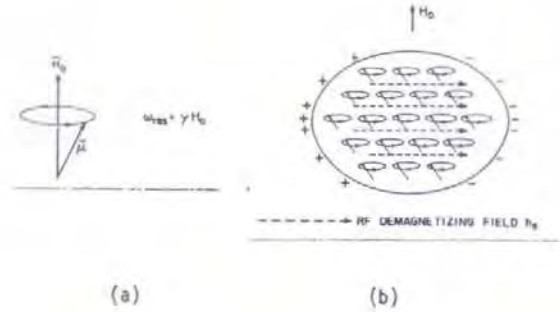

Figure 1. (a) Precessional resonance of single electron. (b) Resonance in a small ferrimagnetic sample.

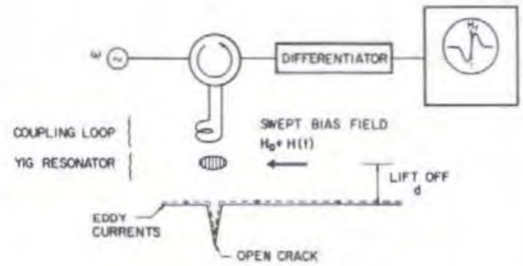

Figure 2. Crack detection in a single swept resonator system. The output indication is sensitive to variations in lift-off.

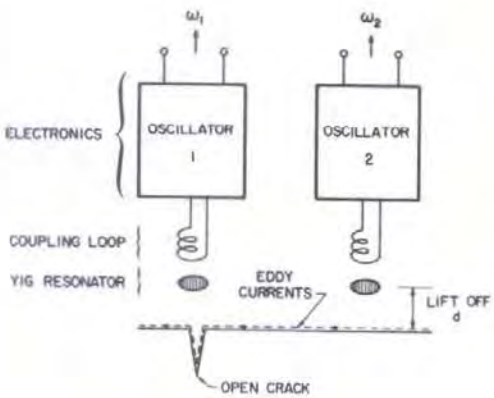

Figure 3. Double resonator system for discrimination against lift-off variations.

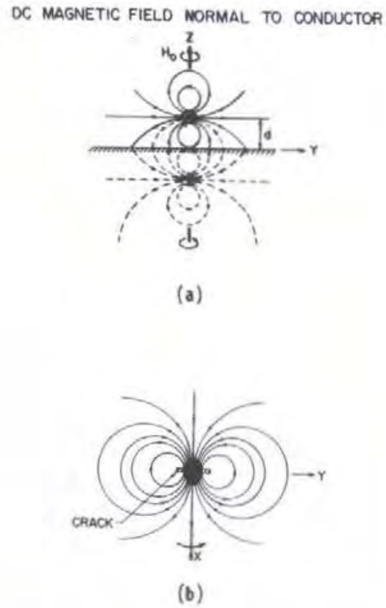

Figure 4. (a) Magnetic field distribution around resonator and its image. (b) Rotating eddy current distribution on conducting wall.

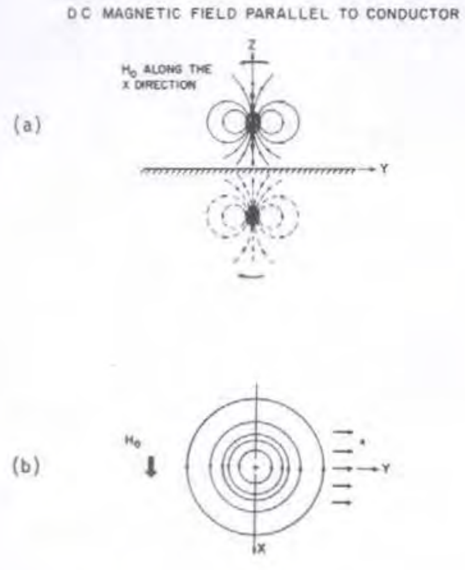

Figure 5. (a) Magnetic field distribution around resonator and its image. (b) Linearly traveling eddy current distribution.

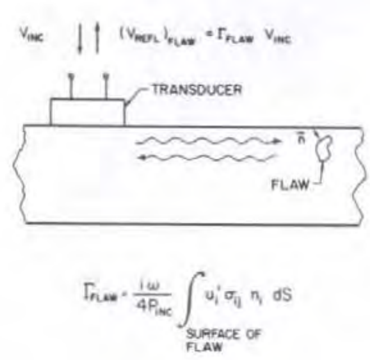

Figure 6. The basic formula for intermode scattering, obtained by reciprocity relation analysis relates the electrical reflection coefficient to a simple integral over the surface of the flaw.

u_i' = displacement in the presence of the flaw due to an electrical input power P_{INC}

σ_{ij} = stress in the absence of the flaw with the same electrical input power.

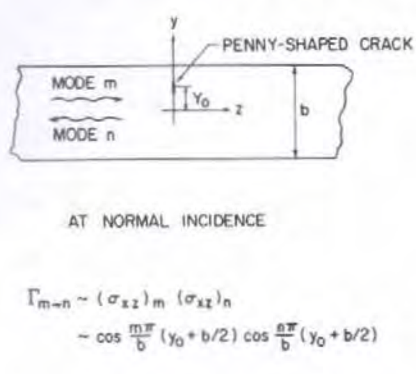

Figure 7. Intermode scattering of SH modes in plates: In the quasistatic approximation of the scattering coefficient is proportional to the product of the model stress at the position of the crack. Measurement of the relative amplitudes and phases of scattering from the m = 0 mode to three higher modes is sufficient to fix the distance Y_0.

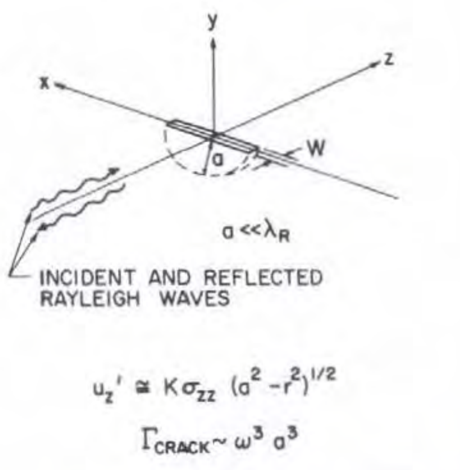

Figure 8. Long wavelength Rayleigh wave scattering by a penny-shaped crack: In this limit only the stress component σ_{zz} of the Rayleigh wave has non-negligible amplitude, and only a single stress intensity factor is required in the quasistatic approximation. The displacement distribution over the half-crack on the surface can be reasonably approximated by that of a full crack (George C. Sih, "Methods of Analysis and Solutions of Crack Problems," Nordhoff, 1973).